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Dynamical Breaking of  $SU(2) \times U(1)$   
and Small Dirac Neutrino Mass

(Seminar at KITP, UCSB, 17 April 2003)

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Plan of the talk :

1. Introduction & motivations
2. Dynamical Breaking of  $SU(2) \times U(1)$   
 (or) EW theory without elementary scalars  
 GR & P N Swamy (work in progress)
3. Small Dirac Mass for Neutrino (with Composite Higgs)  
 P P Divakaran & GR (hep-ph/9901305  
 & Mod. Phys. Lett)

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Introduction

• Success of the Standard Model of HEP

• Big gap

•  $M_H \gtrsim 100 \text{ GeV}$

• Intensive research (what, if H does not exist?)

• Irony of Nature

• SM without elementary scalar field.

Problems with elementary scalars

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- (a) Proliferation of arbitrary parameters. (papers?)  
Predictive power of gauge theory lost.  
Beauty of gauge unification lost.
- (b) Hierarchy or Fine Tuning Problem ( $\rightarrow$  SUSY)
- (c) Triviality of Higgs couplings
- (d) Hawking's argument.

The Problem of the Neutrino Mass

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- The various indications from experiments suggest that neutrinos have very tiny masses (a few eV or less)
- See-saw mechanism is generally thought to be the explanation for such tiny masses. But this requires the neutrinos to be Majorana fermions. ( $\bar{\nu} = \nu$ )
- On the other hand, the increasingly severe limits that are now coming from the nonobservation\* of neutrinoless double beta decay may soon imply that neutrinos are not Majorana fermions. ( $\bar{\nu} \neq \nu$ )
- If so, how to understand the tiny Dirac masses for the neutrinos?
- Electroweak Theory without Elementary Higgs Bosons may be the answer.

\* However, note Klapdor's result (which is not uncontroversial).

## The case for banishing elementary Higgs (5)

- Neutrinos are unique in the SM. They are the only fermions, a part of which, namely the right-handed part  $\nu_R$ , has zero q.nos under  $SU(3) \times SU(2) \times U(1)$  and as a consequence has no gauge interaction.
- Hence, if there are no elementary Higgs bosons, and if the W, Z, quarks & charged leptons get their masses by dynamical breaking of symmetry induced by the  $SU(3) \times SU(2) \times U(1)$  gauge forces alone, then  $\nu$ 's will remain massless.
- In such a case, new interactions going beyond SM will be required for giving mass to  $\nu$ . If the mass scale of the new physics beyond SM is large enough,  $m_\nu$  will remain small. This would provide a natural mechanism for small  $m_\nu$ .
- In contrast, totally arbitrary masses would result from the introduction of elementary Higgs boson.  
So, we discard elementary Higgs.

Usually  $\nu_R$  is banished!

## EW Theory without elementary Higgs (6)

### 1. History

Jackiw & Johnson 1972

Schwinger 1962

Cornwall & Norton 1972

R. Acharya & P N Swamy

H. Pagels

### 2. Results

### 3. Some derivations

Results

(7)

1.  $m_W^2 = m_Z^2 \cos^2 \theta_W$

2.  $m_t$  is of the same order of magnitude as  $m_W$  or  $m_Z$ 

3. Neutrinos remain massless, even after sym breaking

→ Contrast with the usual scenario (with elementary Higgs)

The Electroweak Interactions

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$$\mathcal{L}_{int} = g \vec{W}_\mu \cdot \vec{J}_\mu + g' B_\mu J_\mu^Y$$

$$\vec{J}_\mu = (\bar{\Psi}_1, \bar{\Psi}_2) \gamma_\mu \frac{(1-\gamma_5)}{2} \frac{\tau}{2} \begin{pmatrix} \Psi_1 \\ \Psi_2 \end{pmatrix}$$

$$J_\mu^Y = J_\mu^{em} - J_\mu^3$$

$$Q_1 = \frac{2}{3} \text{ for quarks} \\ = 0 \text{ for leptons}$$

$$J_\mu^{em} = Q_1 \bar{\Psi}_1 \gamma_\mu \Psi_1 + (Q_1 - 1) \bar{\Psi}_2 \gamma_\mu \Psi_2$$

$$J_\mu^3 = \frac{1}{4} \bar{\Psi}_1 \gamma_\mu (1-\gamma_5) \Psi_1 - \frac{1}{4} \bar{\Psi}_2 \gamma_\mu (1-\gamma_5) \Psi_2$$

$$\begin{aligned} \mathcal{L}_{int} &= g \sin \theta_W J_\mu^{em} A_\mu + \frac{g}{\sqrt{2}} \{ J_\mu^- W_\mu^+ + J_\mu^+ W_\mu^- \} \\ &\quad + \frac{g}{\cos \theta_W} \{ J_\mu^3 - \sin^2 \theta_W J_\mu^{em} \} Z_\mu \\ &= e \{ Q_1 \bar{\Psi}_1 \gamma_\mu \Psi_1 + (Q_1 - 1) \bar{\Psi}_2 \gamma_\mu \Psi_2 \} A_\mu \\ &\quad + \frac{g}{2\sqrt{2}} \{ \bar{\Psi}_2 \gamma_\mu (1-\gamma_5) \Psi_1 W_\mu^+ + \bar{\Psi}_1 \gamma_\mu (1-\gamma_5) \Psi_2 W_\mu^- \} \\ &\quad + \frac{g}{2 \cos \theta_W} \{ \bar{\Psi}_1 \gamma_\mu (a - b\gamma_5) \Psi_1 + \bar{\Psi}_2 \gamma_\mu (c + b\gamma_5) \Psi_2 \} Z_\mu \end{aligned}$$

where  $a = \frac{1}{2} - 2 \sin^2 \theta_W Q_1$  ;  $b = \frac{1}{2}$

$$c = -\frac{1}{2} - 2 \sin^2 \theta_W (Q_1 - 1)$$

$$W_\mu^\pm = \frac{1}{\sqrt{2}} (W_\mu^1 \pm i W_\mu^2)$$

$$Z_\mu = \sin \theta_W B_\mu - \cos \theta_W W_\mu^3$$

$$A_\mu = \cos \theta_W B_\mu + \sin \theta_W W_\mu^3$$

$$\tan \theta_W = \frac{g'}{g}$$

$$e = g \sin \theta_W$$

Dyson-Schwinger Eqs

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$$S_1^{-1}(p) = \not{p} - ie^2 Q_1^2 \int \frac{d^4 k}{(2\pi)^4} D_{\mu\nu}^E(p-k) \gamma^\mu S_1(k) \Gamma_{E1}^\nu(p,k)$$

$$- i \frac{g^2}{4 \cos^2 \theta_w} \int \frac{d^4 k}{(2\pi)^4} D_{\mu\nu}^Z(p-k) \gamma^\mu (a-b\gamma_5) S_1(k) \Gamma_{Z1}^\nu(p,k)$$

$$- i \frac{g^2}{4} \int \frac{d^4 k}{(2\pi)^4} D_{\mu\nu}^W(p-k) \gamma^\mu (1-\gamma_5) S_2(k) \Gamma_W^\nu(p,k)$$

$$S_2^{-1}(p) = \not{p} - ie^2 (Q_1 - 1)^2 \int \frac{d^4 k}{(2\pi)^4} D_{\mu\nu}^E(p-k) \gamma^\mu S_2(k) \Gamma_{E2}^\nu(p,k)$$

$$- i \frac{g^2}{4 \cos^2 \theta_w} \int \frac{d^4 k}{(2\pi)^4} D_{\mu\nu}^Z(p-k) \gamma^\mu (c+b\gamma_5) S_2(k) \Gamma_{Z2}^\nu(p,k)$$

$$- i \frac{g^2}{4} \int \frac{d^4 k}{(2\pi)^4} D_{\mu\nu}^W(p-k) \gamma^\mu (1-\gamma_5) S_1(k) \Gamma_W^\nu(p,k)$$

$$S_1^{-1} = \not{p} - \Sigma_1(p) = \not{p} - X_1(p^2) + \gamma_5 N_1(p^2) - \gamma_5 \not{p} R_1(p^2)$$

$$S_1 = \not{p} A_1 + B_1 + \not{p} \gamma_5 C_1 + \gamma_5 D_1$$

where  $A_1 = \frac{1}{p^2(1-R_1^2) - (X_1^2 - N_1^2)}$

$$B_1 = X_1 A_1$$

$$C_1 = R_1 A_1$$

$$D_1 = N_1 A_1$$

Similarly for  $S_2$

All vertex functions  $\Gamma_\mu \rightarrow$  bare vertices ( $\gamma_\mu, \gamma_\mu \gamma_5 \dots$ )

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$$S_1^{-1} = \not{p} - ie^2 Q_1^2 \int \frac{d^4 k}{(2\pi)^4} D_{\mu\nu}^E(q) \gamma^\mu S_1(k) \gamma^\nu$$

$\rightarrow p-k$

$$- i \frac{g^2}{4 \cos^2 \theta_w} \int \frac{d^4 k}{(2\pi)^4} D_{\mu\nu}^Z(q) [(a^2+b^2) \gamma^\mu \not{K} (A_1 + \gamma_5 C_1) \gamma^\nu$$

$$+ (a^2-b^2) \gamma^\mu (B_1 + \gamma_5 D_1) \gamma^\nu + 2ab \gamma^\mu \not{K} (A_1 + \gamma_5 C_1) \gamma_5 \gamma^\nu]$$

$$- i \frac{g^2}{8} \int \frac{d^4 k}{(2\pi)^4} D_{\mu\nu}^W(q) [\frac{1}{2} \gamma^\mu \not{K} (A_2 + \gamma_5 C_2) \gamma^\nu$$

$$- \frac{1}{2} \gamma^\mu \gamma_5 \not{K} (A_2 + \gamma_5 C_2) \gamma^\nu]$$

All vector propagators  $\rightarrow$  bare propagators

$$R_1(p^2) = 0$$

$$S_1(p) = \{ \not{p} + X_1(p^2) + \gamma_5 N_1(p^2) \} \frac{1}{p^2 - M_1^2(p^2)}, \text{ where } M_1^2 \equiv X_1^2 - N_1^2$$

$$M_1(p^2) = -i \frac{\lambda_1}{\pi^2} \int d^4 k \frac{M_1(k^2)}{(p-k)^2 [k^2 - M_1^2(k^2)]}$$

"Gap" Equation

where  $\lambda_1 = \frac{3}{16\pi^2} [e^2 Q_1^2 + \frac{1}{4} (a^2 - b^2) (g^2 + g'^2)]$

$$M_1^2(p^2 = m_1^2) = m_1^2$$

$$a = \frac{1}{2} - 2 \sin^2 \theta_w Q_1$$

$$b = \frac{1}{2}$$

Neutrinos :

$$Q_1 = 0; a = b = \frac{1}{2}$$

$$m_\nu = 0$$

Ward-Takahashi identities

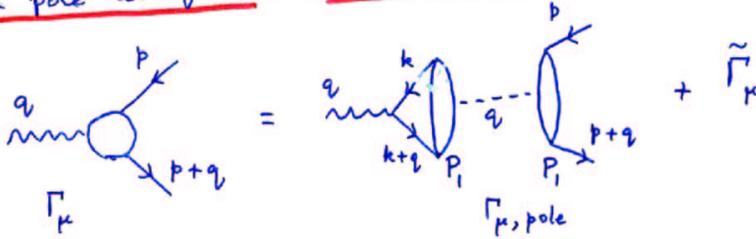
(11)

$$q_\mu \Gamma_\mu^1(p, p+q) = -b [\gamma_5 \bar{S}_1'(p+q) + \bar{S}_1'(p) \gamma_5] + a [\bar{S}_1'(p+q) - \bar{S}_1'(p)]$$

$$q_\mu \Gamma_\mu^2(p, p+q) = b [\gamma_5 \bar{S}_2'(p+q) + \bar{S}_2'(p) \gamma_5] + c [\bar{S}_2'(p+q) - \bar{S}_2'(p)]$$

$$q_\mu \Gamma_\mu^W(p, p+q) = - [\gamma_5 \bar{S}_1'(p+q) + \bar{S}_2'(p) \gamma_5] + [\bar{S}_1'(p+q) - \bar{S}_2'(p)]$$

If the fermions are massive, the vertex functions develop a pole at  $q^2 = 0$ . (Goldstone Boson)



$$\Gamma_{\mu, pole}^1(p, p+q) = \left[ \text{Tr} \int \frac{d^4 k}{(2\pi)^4} S_1(k) \gamma_\mu (a - b\gamma_5) S_1(k+q) P_1(k+q, k) \right] \frac{i}{q^2} P_1(p, p+q)$$

$v_\mu I_1(q^2)$

$$\Gamma_{\mu, pole}^2(p, p+q) = \left[ \text{Tr} \int \frac{d^4 k}{(2\pi)^4} S_2(k) \gamma_\mu (c + b\gamma_5) S_2(k+q) P_2(k+q, k) \right] \frac{i}{q^2} P_2(p, p+q)$$

$v_\mu I_2(q^2)$

$$\Gamma_{\mu, pole}^W(p, p+q) = \left[ \text{Tr} \int \frac{d^4 k}{(2\pi)^4} S_1(k) \gamma_\mu (1 - \gamma_5) S_2(k+q) P_W(k+q, k) \right] \frac{i}{q^2} P_h(p, p+q)$$

$v_\mu I_W(q^2)$

Generation of vector boson masses

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(The dynamical Higgs mechanism, or, Schwinger mechanism)

$$D_{\mu\nu}(q) = -i \left( g^{\mu\nu} - \frac{q^\mu q^\nu}{q^2} \right) \frac{1}{q^2 - q^2 \Pi(q^2)}$$

$$\Pi_{\mu\nu}(q) \equiv - \int d^4 x e^{iq \cdot x} \langle 0 | T (J^\mu(x) J^\nu(0)) | 0 \rangle$$

$$= i \left( g^{\mu\nu} - \frac{q^\mu q^\nu}{q^2} \right) \Pi(q^2) = i (q^2 g^{\mu\nu} - q^\mu q^\nu) \Pi(q^2)$$

If  $\Pi(q^2)$  has a pole at  $q^2 = 0$ , the vector boson is massive

Ward-Takahashi identity:

$$q_\mu \Gamma^\mu(p, p+q) = \gamma_5 \bar{S}'(p+q) + \bar{S}'(p) \gamma_5$$

Let chiral sym be spontaneously broken and fermion pick up mass.  $\bar{S}' = -i (\not{x} - \Sigma(p))$   $\{\gamma_5, \Sigma(p)\} \neq 0$

$$\lim_{q \rightarrow 0} q_\mu \Gamma^\mu(p, p+q) = -i \{\gamma_5, \Sigma(p)\} \neq 0$$

$\therefore \Gamma^\mu(p, p+q)$  has a pole at  $q^2 = 0$

$$\begin{aligned} \Gamma_{\mu, pole}^\mu(p, p+q) &= - \left[ \text{Tr} \int \frac{d^4 \tau}{(2\pi)^4} S(\tau) i \gamma^\mu \gamma_5 S(\tau+q) P(\tau+q, \tau) \right] \frac{i}{q^2} P(p, p+q) \\ &= i \frac{q^\mu}{q^2} I(q^2) P(p, p+q) \end{aligned}$$

Combining,  $I(0) P(p, p) = \{\gamma_5, \Sigma(p)\}$

Schwinger-Dyson Eq. for vec. pol. tensor

(13)

$$\text{wavy line} = \text{wavy line} \text{---} \text{loop} \text{---} \text{wavy line}$$

$\Pi^{\mu\nu} \qquad \qquad \qquad \Gamma^{\mu}$

Since  $\Gamma^{\mu}$  has a pole at  $q^2=0$ ,  $\Pi^{\mu\nu}$  also develops a pole.

Insert the  $\Gamma^{\mu}$  pole to get the  $\Pi^{\mu\nu}$  pole.

$$\begin{aligned} \Pi^{\mu\nu}_{\text{pole}} &= \text{wavy line} \text{---} \text{loop} \text{---} \text{wavy line} \\ &= q^{\mu} I(q^2) \frac{1}{q^2} q^{\nu} I(q^2) \Big|_{q^2=0} \\ &= I^2(0) \frac{q^{\mu} q^{\nu}}{q^2} \end{aligned}$$

$$\Rightarrow \Pi_{\text{pole}}(q^2) = \frac{I^2(0)}{q^2}$$

$$D^{\mu\nu}(q) = -i \left( g^{\mu\nu} - \frac{q^{\mu} q^{\nu}}{q^2} \right) \frac{1}{q^2 - I^2(q^2)}$$

$$\therefore M_V^2 = I^2(0)$$

Thus, the vector boson eats the Goldstone boson and becomes massive. Also, one can show that the object with  $q^2=0$  decouples from the physical spectrum. This is the dynamical Higgs mechanism (or Higgs mechanism without elementary Higgs scalar) — actually, Schwinger mechanism, since he had pointed out its possibility earlier.

$$\Gamma^{\mu}_{\text{pole}}(p, p+q) = \frac{q_{\mu}}{q^2} I_1(q^2) P_1(p, p+q)$$

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& similarly for others.

$$\lim_{q \rightarrow 0} q^{\mu} \Gamma^{\mu}_{\text{pole}}(p, p+q) = I_1(0) P_1(p, p)$$

$$\lim_{q \rightarrow 0} q^{\mu} \Gamma^{\mu 2}_{\text{pole}}(p, p+q) = I_2(0) P_2(p, p)$$

$$\lim_{q \rightarrow 0} q^{\mu} \Gamma^{\mu W}_{\text{pole}}(p, p+q) = I_W(0) P_W(p, p)$$

From the W-T identities,

$$\lim_{q \rightarrow 0} q^{\mu} \Gamma^{\mu}_1(p, p+q) = -b \{ \gamma_5, \bar{S}'_1(p) \}$$

$$\lim_{q \rightarrow 0} q^{\mu} \Gamma^{\mu 2}_1(p, p+q) = +b \{ \gamma_5, \bar{S}'_2(p) \}$$

$$\lim_{q \rightarrow 0} q^{\mu} \Gamma^{\mu W}_1(p, p+q) = -\gamma_5 \bar{S}'_1(p) - \bar{S}'_2(p) \gamma_5 + \bar{S}'_1(p) - \bar{S}'_2(p)$$

Combining,  $I_1(0) P_1(p, p) = -b \{ \gamma_5, \bar{S}'_1(p) \}$

$$I_2(0) P_2(p, p) = b \{ \gamma_5, \bar{S}'_2(p) \} \approx 0$$

$$I_W(0) P_W(p, p) = -\gamma_5 \bar{S}'_1(p) - \bar{S}'_2(p) \gamma_5 + \bar{S}'_1(p) - \bar{S}'_2(p)$$

$$\begin{aligned} [I_1(0)]^2 &= -2i b^2 (g^2 + g'^2) \int \frac{d^4 k}{(2\pi)^4} \frac{M_1^2(k^2)}{[k^2 - M_1^2(k^2)]^2} \\ [I_W(0)]^2 &= -\frac{i}{2} g^2 \int \frac{d^4 k}{(2\pi)^4} \frac{M_1^2(k^2)}{k^2 [k^2 - M_1^2(k^2)]} \end{aligned}$$

Electroweak Theory without Higgs

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(with P. Narayana Swamy, SIUE, USA)

Step 1 Dyson-Schwinger Eq:



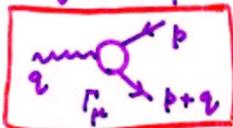
$$M(q^2) = -i \frac{\lambda_1}{\pi^2} \int d^4k \frac{M(k^2)}{(p-k)^2 [k^2 - M^2(p^2)]}$$

"Gap" Eq.

where  $\lambda_1 = \frac{3}{16\pi^2} [e^2 Q_1^2 + \frac{1}{4}(a^2 - b^2)(g^2 + g'^2)]$   
 $a = \frac{1}{2} - 2 \sin^2 \theta_W Q_1$ ;  $b = \frac{1}{2}$

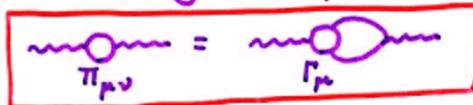
For neutrinos,  $Q_1 = 0$ ;  $a = b = \frac{1}{2} \Rightarrow m_\nu = 0$

Step 2 Use Ward-Takahashi identities to show that if the fermions are massive, the vertex functions  $\Gamma_\mu$



develop a pole at  $q^2 = 0$  (Goldstone Boson)

Step 3 Use the Dyson-Schwinger Eqs for the vac. pol. tensors  $\pi_{\mu\nu}$



to show that the vector bosons W and Z eat the Goldstone bosons and become massive.

This is the Dynamical Higgs Mechanism, or Higgs mechanism without elementary Higgs scalar - actually

Solution of the "gap equation"

(16)

$$M_1(p^2) = -i \frac{\lambda_1}{\pi^2} \int d^4k \frac{M_1(k^2)}{(p-k)^2 [k^2 - M_1^2(k^2)]}$$

$$p^2 = p_0^2 - \vec{p}^2$$

Go to Euclidean metric:  $k_0 \rightarrow ik_0$

$$M_1(-p^2) = \frac{\lambda_1}{\pi^2} \int d^4k \frac{M_1(-k^2)}{(p-k)^2 [k^2 + M_1^2(-k^2)]}$$

where all momenta are Euclidean 4-vectors

$$M_1(-p^2 = m_1^2) = m_1 \quad (\text{B.C.})$$

MHJ\* approx: Replace  $M_1(-k^2)$  in the Dr by  $m_1$

The soln. which satisfies the above B.C. and is finite at the origin is

$$M_1(-p^2) = m_1 \lambda_1 \pi \sec \frac{\pi \nu_1}{2} F\left(\frac{1+\nu_1}{2}, \frac{1-\nu_1}{2}, 2; -\frac{p^2}{m_1^2}\right)$$

where  $\nu_1 = (1 - 4\lambda_1)^{1/2}$

\* Marc, Herscovitz & Jacob (PRL, 1964)

Vector Boson Masses

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$$M_Z^2 = -2ib^2(g^2 + g'^2) \int \frac{d^4k}{(2\pi)^4} \frac{[M_1(k^2)]^2}{(k^2 - M_1^2)^2}$$

$$M_W^2 = -\frac{i}{2}g^2 \int \frac{d^4k}{(2\pi)^4} \frac{[M_1(k^2)]^2}{k^2(k^2 - M_1^2)}$$

- Transform to Euclidean metric
- Substitute  $M_1(-k^2) = m_1 \lambda_1 \pi \sec \frac{\pi \nu_1}{2} F\left(\frac{1+\nu_1}{2}, \frac{1-\nu_1}{2}; 2; -\frac{k^2}{m_1^2}\right)$
- MHJ approx:  $[M(-k^2)]^2 \approx m_1 M_1(-k^2)$  in Nr  
 $k^2 + M_1^2(k^2) \approx k^2 + m_1^2$  in Dr

$$M_Z^2 = \frac{b^2(g^2 + g'^2)}{8} \lambda_1^2 \pi^2 m_1^2 \left(\sec \frac{\pi \nu_1}{2}\right)^3$$

$$M_W^2 = \frac{g^2}{32} \lambda_1 m_1^2 \left(\sec \frac{\pi \nu_1}{2}\right)^2$$

Where  $\lambda_1 = \frac{3}{16\pi^2} \left[ e^2 \Phi_1^2 + \frac{1}{4}(a^2 - b^2)(g^2 + g'^2) \right] = \frac{3g'^2}{16\pi^2} \Phi_1 \left(\Phi_1 - \frac{1}{2}\right)$   
 $\nu_1 = (1 - 4\lambda_1)^{1/2}$

$$\frac{g'^2}{4\pi} \approx \frac{1}{103} \quad \therefore \lambda_1 \ll 1$$

$$\nu_1 \approx 1 - 2\lambda_1; \quad \sec \frac{\pi \nu_1}{2} \approx \frac{1}{\pi \lambda_1}$$

Results:

- ①  $\frac{M_W^2}{M_Z^2} = \cos^2 \theta_W$
- ②  $m_t^2 = \frac{2}{3} \tan^2 \theta_W M_W^2 = \frac{2}{9} M_W^2$  or,  $m_t \approx 0.47 M_W \approx 38 \text{ GeV}$
- ③  $m_\nu = 0$

$$M_W^2 = \sum_i C_i m_i^2 \approx C_t m_t^2$$

$$M_Z^2 = \sum_i d_i m_i^2 \approx d_t m_t^2$$

• ...

Composite Higgs and Small Dirac  $\nu$  mass (18)

- To make this dynamical SB a little more concrete, let us envisage a picture in which the Higgs boson H is a composite of f and  $\bar{f}$  bound by the SU(3) x SU(2) x U(1) gauge forces through some nonperturbative mechanism.

$$H \sim \bar{t}_L t_R, \bar{b}_L b_R \dots \bar{d}_L d_R, \bar{\nu}_L \nu_R \dots \bar{e}_L e_R$$

but not  $\bar{\nu}_L \nu_R$  ( $\because \nu_R$  has no gauge interaction)

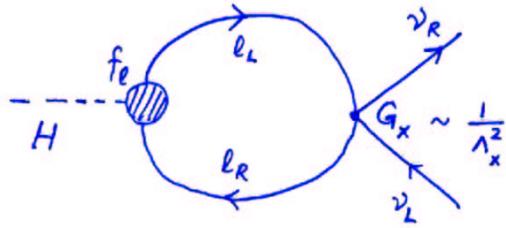
In other words,

the effective Yukawa coupling  $H \bar{\nu}_L \nu_R$  vanishes identically, to all orders in the SU(3) x SU(2) x U(1) gauge coupling constants.

- On the other hand, the effective Yukawa vertex  $H \bar{e}_L e_R \dots$  exists and it has a form factor characterized by a mass scale  $\Lambda_{SM} \approx 100 \text{ GeV}$ .
- If H has a nonvanishing v.e.v, masses of the charged fermions are "allowed", while  $\nu$  masses are "forbidden" in the SM.
- So, the only way to make  $\nu$  massive, is to invoke forces beyond SM.

General idea

(19)



$$f_\nu \approx f_e G_x \int \frac{d^4 p}{\not{p} \not{p}} \approx f_e G_x \Lambda_H^2 = f_e \left( \frac{\Lambda_H}{\Lambda_x} \right)^2$$

$$m_\nu = f_\nu \langle H \rangle ; m_e = f_e \langle H \rangle$$

$$\Rightarrow \boxed{m_\nu \approx m_e \left( \frac{\Lambda_H}{\Lambda_x} \right)^2}$$

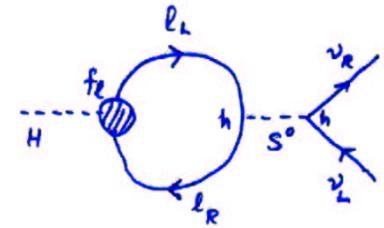
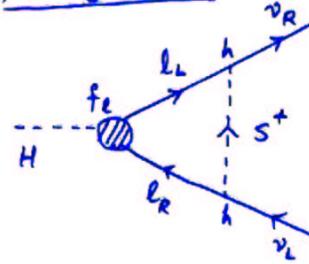
$$\Lambda_H \sim 100 \text{ GeV}$$

$$m_e \sim 100 \text{ MeV} ; m_\nu \sim 1 \text{ eV}$$

$$\Rightarrow \Lambda_x \sim 10^6 \text{ GeV}$$

Examples  
(a) Heavy scalars

(20)



$$G_x \approx \frac{h^2}{m_s^2}$$

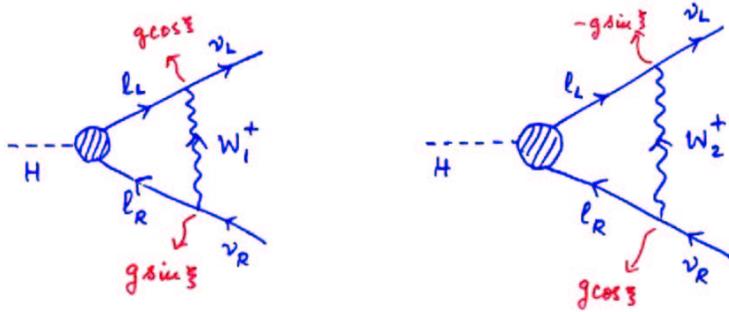
b)  $SU(2)_L \times SU(2)_R \times U(1)$

$$W_1 = W_L \cos \xi + W_R \sin \xi$$

$$W_2 = -W_L \sin \xi + W_R \cos \xi$$

$$|\xi| < 10^{-2} - 10^{-3}$$

$$\beta \equiv \left(\frac{m_{W_1}}{m_{W_2}}\right)^2 < 0.02$$



$$G_x \approx g^2 \cos \xi \sin \xi \left( \frac{1}{m_{W_1}^2} - \frac{1}{m_{W_2}^2} \right)$$

$$\approx \left( \frac{\xi}{\beta} \right) \frac{g^2}{m_{W_2}^2} \ll \frac{g^2}{m_{W_2}^2}$$

$$\Rightarrow m_{W_2} \approx 10^4 - 10^5 \text{ GeV}$$

(21)

To sum up,

(22)

